

# ANALYSIS OF ACOUSTIC PRESSURE OSCILLATION DURING VENTED DEFLAGRATION

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## ABSTRACT

In industrial buildings explosion relief panels or doors are often used to reduce damages caused by gas explosion. Decades of research produced a significant contribution to the understanding of the phenomena involved, nevertheless, among the aspects that need further research, interaction between acoustic oscillation and the flame front is one of the more important. Interaction between the flame front and acoustic oscillation has raised technical problem in lots of combustion applications as well, and had been studied theoretically and experimentally in such cases. Pressure oscillation had been observed in vented deflagration and in certain cases they are responsible for the highest pressure peak generated during the event. At Scalbatraio laboratory of Pisa University CVE test facility was built in order to investigate vented hydrogen deflagration. This paper is aimed to present an overview of the results obtained during several experimental campaigns which tests are analysed with the focus on the investigation of flame acoustic interaction phenomenon. Qualitative and quantitative analysis is presented and the possible physic generating the phenomenon investigated.

**Key words:** Hydrogen, Vent, Deflagration, Flame acoustic interaction

## 1. INTRODUCTION

A deflagration essentially involves an unsteady premixed flame front that develops from an ignition source and travels through a medium which may involve complex boundary conditions and obstructions of various geometries, generating an overpressure that can cause damages to personnel and structures. In practical situations venting is often used as a measure to prevent damages to the structures in an unlikely event of a deflagration, hence the understanding of the phenomenon is a critical issue for their safe design.

The study of confined vented deflagrations is a very complex topic as many parameters affect their behaviour, i.e.: inhomogeneous concentration of the gas in the environment, volume's geometry, presence of obstacles within the environment, location, size and strength of the vent, position of the ignition source, pre-ignition turbulence, etc. One of the phenomena involved in vented deflagration is the interaction between the flame and acoustic oscillation that are generated during the process. Many authors who have contributed to the research in vented deflagrations report that oscillatory pressure peak are attained during the deflagration which may be attributed to coupling of the acoustic waves with the flame front [1,2,3,4,5,6,7].

Coupling mechanisms between acoustic waves and flames have also become central issues in the development of many modern combustion devices and extensive research has been performed in the field focusing on stationary premixed flames such as the one involved in burners [9,10,11] and gas turbines [8].

Acoustic waves can be self-produced by the expanding flame [9], but the flame front can also interact and be influenced by acoustic waves generated by other mechanisms. Research has underlined that in combustors different possible mechanisms exists through which a flame can be affected by acoustic; one is through pressure variations, which lead to modification of the laminar flame speed and to combustion instabilities when these variations and fluctuations of the heat release rate obey the Rayleigh criterion, a second mechanisms is through oscillation of the flame area induced by the acoustic accelerations, a third mechanisms is through oscillation of the equivalent ratio (this mode being involved particularly when the

fuel is injected as a liquid), and a fourth one through oscillation of the flame area induced by convective effects [10].

Even though in vented deflagrations the generated overpressure can be affected by an oscillatory behaviour as well as in combustors, the physic of the phenomenon can be considered different due to the hydrodynamic field involved.

The performed experiments show that pressure oscillation are triggered inside the vented volume after the flame front reaches the vent area, producing an high discharge rate that prompts acoustic resonances at frequencies characteristic of the enclosure. The mechanism of interaction between the flame front and the acoustic oscillation may be due to the acoustic accelerations.

Following this scenario the flame front can be seen as an interface separating two fluids of different densities. The flame front will than react to the imposed acceleration field as well as it does to gravity. In fact in the presence of acoustic velocity field the flame front is subjected to an oscillating acceleration, when this acceleration is oriented toward the burnt gas the amplitude of the reaction zone will tend to decrease, while when it is oriented towards the unburnt gas, the amplitude of the reaction zone will tend to increase. In this way the acoustic field can thus modulate the total instantaneous heat release rate.

This paper presents the analysis of experimental vented deflagration tests where flame acoustic interaction is involved and suggests a possible interpretation of the phenomenon.

## 2. EXPERIENTIAL CAMPAIGNS

The CVE (Chamber View Explosion) apparatus is a nearly cubic structure characterized by an internal volume of about 25 m<sup>3</sup>; the roof and one side face are entirely covered with panels of glass (see Figure 1a) which allow to video record the flame, more details can be found in previous publications [5,6,7].

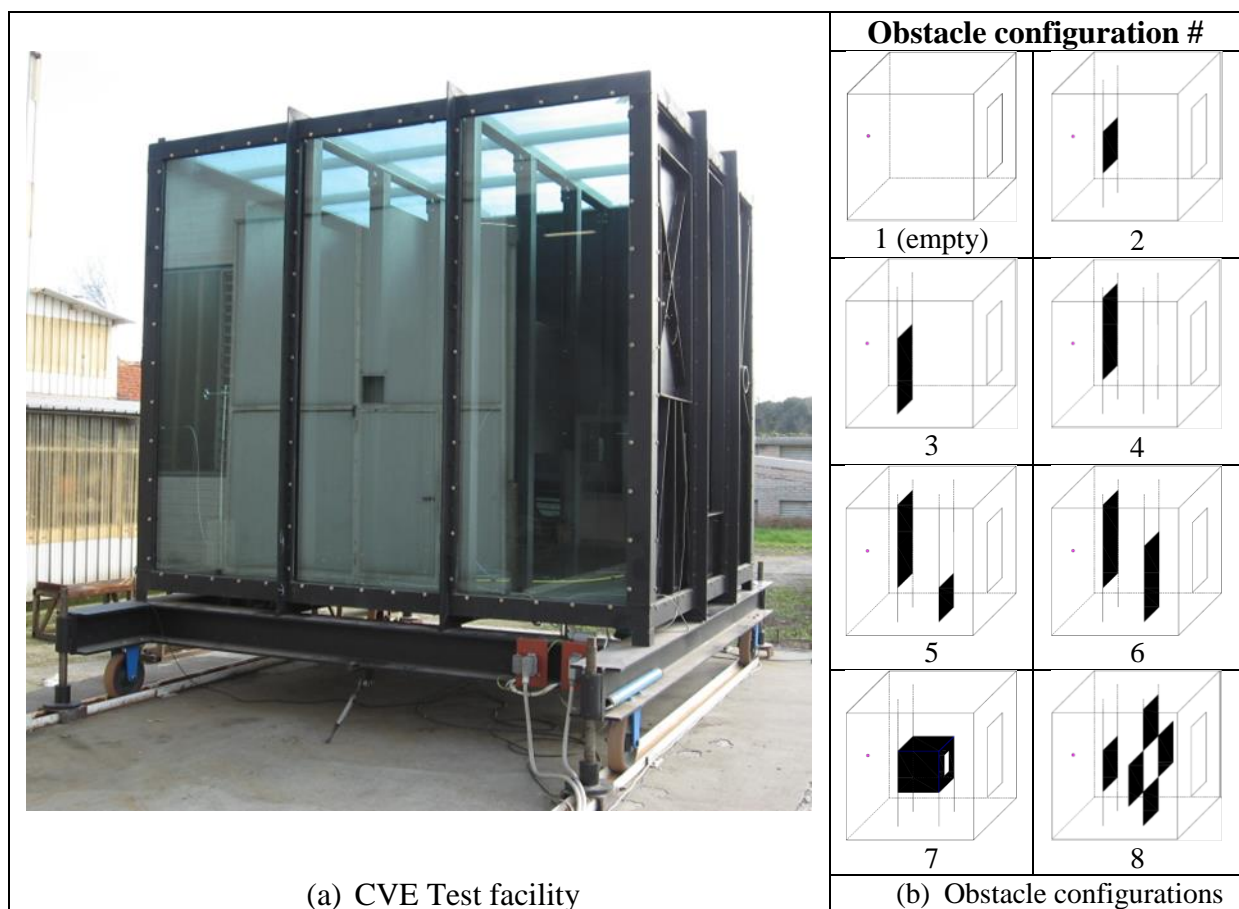


Figure 1 – (a) Photo of the CVE test facility and (b) internal obstacle configurations

CVE has been built in order to perform vented deflagration tests. In the experimental campaigns which results are presented in this paper the vent dimensions were kept fixed and characterized by a width of 0,62 m and an height of 1,62 m (vent area 1,0044 m<sup>2</sup>). The vent area was closed with a plastic sheet having an opening pressure of approximately 2.4 kPa.

Inside the CVE test facility different kind of obstacles had been placed (see Figure 1b), test collected and analysed in this paper were performed during various experimental campaign, one of which, called Reduced CVE campaign (RED-CVE), involved the presence of a smaller box of 0.68 m<sup>3</sup> volume placed inside the test facility [6]. The vent of the inner box was kept constantly open, while the vent area could be varied having surfaces of 0.027675 m<sup>2</sup> (vent1), 0.042025 m<sup>2</sup> (vent2) or 0.05535 m<sup>2</sup> (vent3).

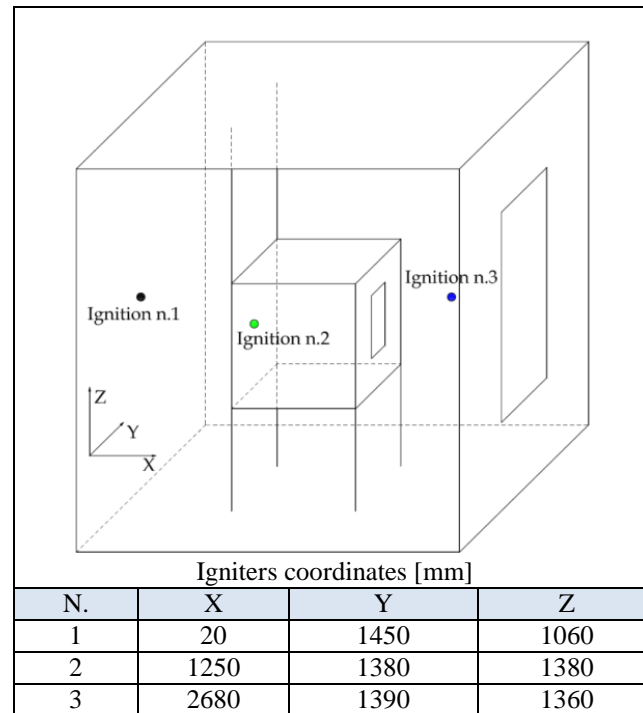


Figure 2 – Ignition location and coordinates (left)

Hydrogen concentrations under investigation ranged between 7% vol. and 13% vol in all the experimental campaigns.

During the release of hydrogen inside the facility the concentration had been homogenized through the use of a fan, at the end of the release phase the fan was turned off conveniently earlier to prevent initial turbulence inside the vented volume. A second fan was used to homogenise the atmosphere inside the RED-CVE box in tests where this configuration was adopted. Despite of the fans, hydrogen concentration showed a stratification behavior inside the facility, with lower concentration at the bottom and higher concentration under the facility ceiling, the difference of concentrations measured between the lower and the upper sampling points was about 1,5 % vol. in every tests.

In the cited RED-CVE campaign three different ignition location were tested, the first of which was located on the CVE's side opposite to the vent at 1 m high from the floor, the second inside the RED-CVE box and the third in between the RED-CVE box and the vent (see Fig.2).

Pressure transducer were placed in the centre of the wall opposite the vent and in the centre of the wall opposite the glass one, in obstacle's configuration 7, RED-CVE campaign, the second pressure transducer was placed inside the RED-CVE box. Pressure readings were recorded at with a frequency of 5 kHz.

Frequency analysis was performed through Discrete Fourier Transform of the signals recorded by the pressure transducers.

### 3. ACOUSTIC WAVES – FLAME INTERACTION (RESULTS AND DISCUSSION)

In all the tests performed with ignition opposite the vent area and average  $H_2$  concentration higher than 9% vol. the pressure time history inside the CVE test facility showed strong pressure oscillations. It is general belief that these pressure oscillations are generated by the interaction between the flame front and acoustic waves. The analysis performed on the data collected from the tests proved that these oscillations arose after the flame front reached the vent, see Figure 3.

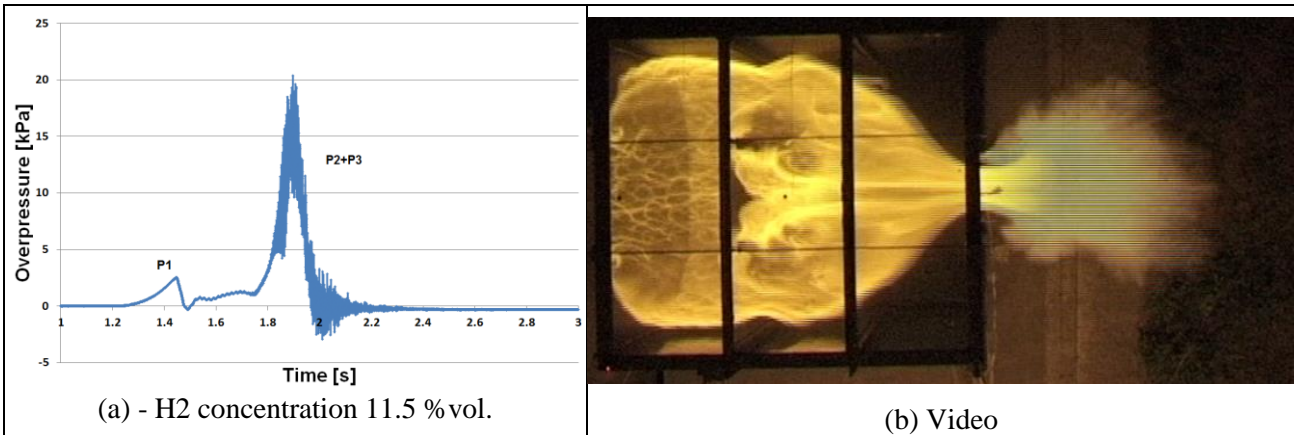


Figure 3 – Pressure time history for tests performed with ignition opposite the vent (a) and photo of the flame inside the CVE test facility (b)

As a matter of fact when the flame reaches the vent a great change is introduced inside the system since the burned mixture starts to flow out of the vent area having a much lower density and abruptly increasing the mass flow rate. This phenomenon was long recognized and addressed to be responsible of a pressure peak attained inside the enclosure. The results of the analysis described in the present paper support the hypothesis that when the flame reaches the vent it induces also a different burning regime in the flame front that continues to expand in direction perpendicular to the vent, which is, after this moment, more prone to be influenced by acoustic oscillation.

The flame expanding inside the volume, before reaching the vent area, can be affected by different flow regime and instabilities, as the Darrenius Landau instabilities, as extensively studied in the past [12]. Nevertheless all kind of acoustic oscillation, either of external origin or self-produced by the expanding flame front, are counteracted by the expansion of the flame front itself. As a matter of fact the assumption leading to the definition of the burning velocity of the expanding flame front involve the expansion factor given by the ratio of the densities of unburnt and burnt gases, taking into account the production of burning products that “pushes” the flame front toward the unburned mixture contributing to stabilize it. After the flame front reaches the vent this assumption is not completely met anymore since the expansion of the burned gases towards the unburned mixture is prevented, or at least decreased, by the flow of burned products exiting the vented volume through the vent area.

If the deflagration had been ignited close to the wall opposite the vent, when the flame front reaches it the burned gases occupy a sort of truncated cone having its base lying on the wall opposite the vent and its edge on the vent area. The combustion products tend to be ejected through the vent area due to the pressure difference between the enclosure and the outer atmosphere. So the combustion products do not influence anymore the flame front in direction perpendicular to the cone axis. During the first phase of the deflagration the influence of the expanding combustion products acts as a stabilizer to the flame front, opposing the acoustic perturbations. The discontinuity produced by the flame reaching the vent area may be than responsible for the change in the burning behaviour of the flame front making it more susceptible to be influenced by the acoustic perturbation. At the same time the abrupt increase of discharge rate may be considered also responsible of triggering acoustic waves at frequencies characteristic of the resonant response the enclosure.

The Figure 4 shows the pressure time history of a test where two pressure transducers were present inside the test facility. The one placed on the lateral wall records pressure oscillations earlier than the one placed on the

wall opposite the vent area. This behaviour is reported in all the tests performed with ignition opposite the vent and is meaningful of how the phenomena inside the enclosure are affected by the flow field generated after the combustion products reached the vent.

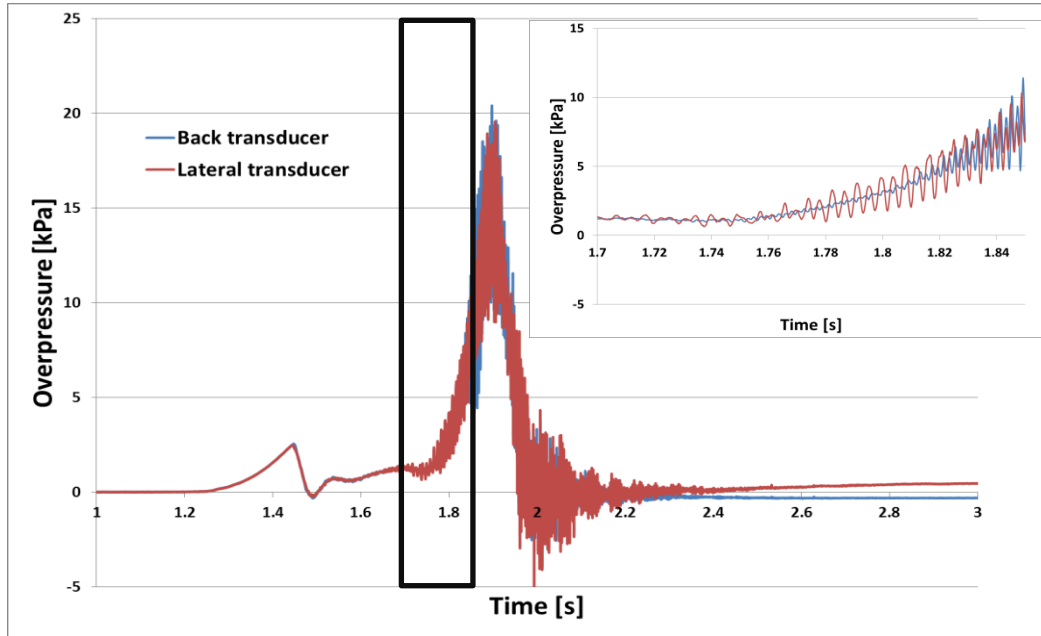


Figure 4 – Detail of pressure oscillations recorded by the two transducers

In order to make more clear the described behaviour, the pressure-time history of some test where the ignition took place inside the RED-CVE box (location 2 in Figure 2) are showed as an example in Figure 5. The vent of the RED-CVE box was open, facing the vent of the CVE facility that was closed by a plastic sheet.

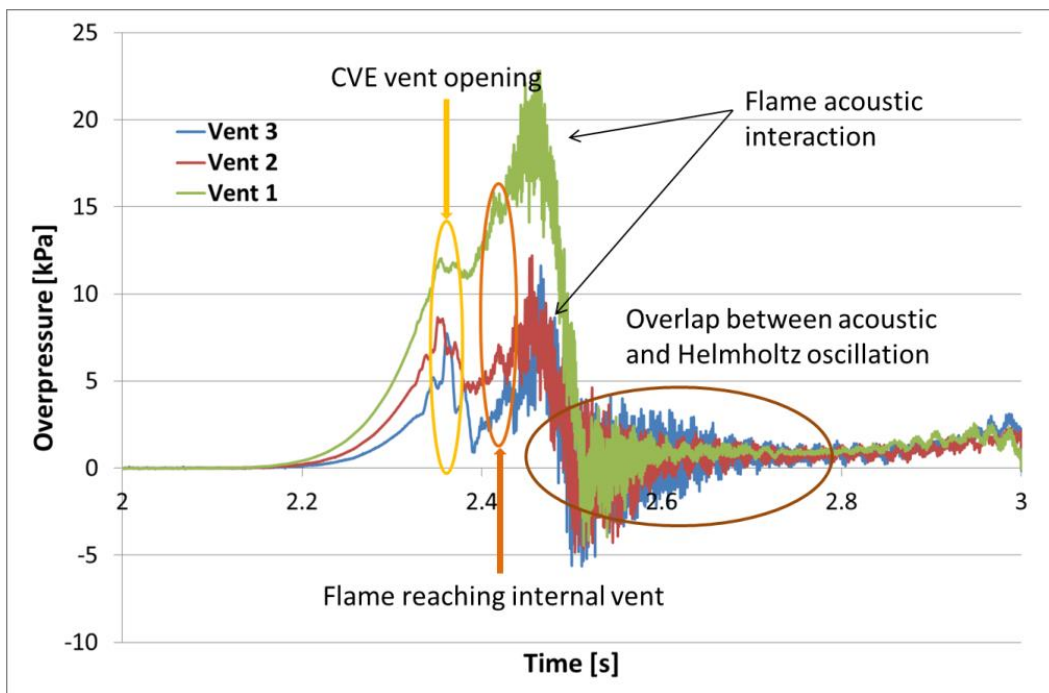


Figure 5 – Pressure-time history of RED-CVE box for  $H_2$  concentration of 11.8% with 3 different vent dimension



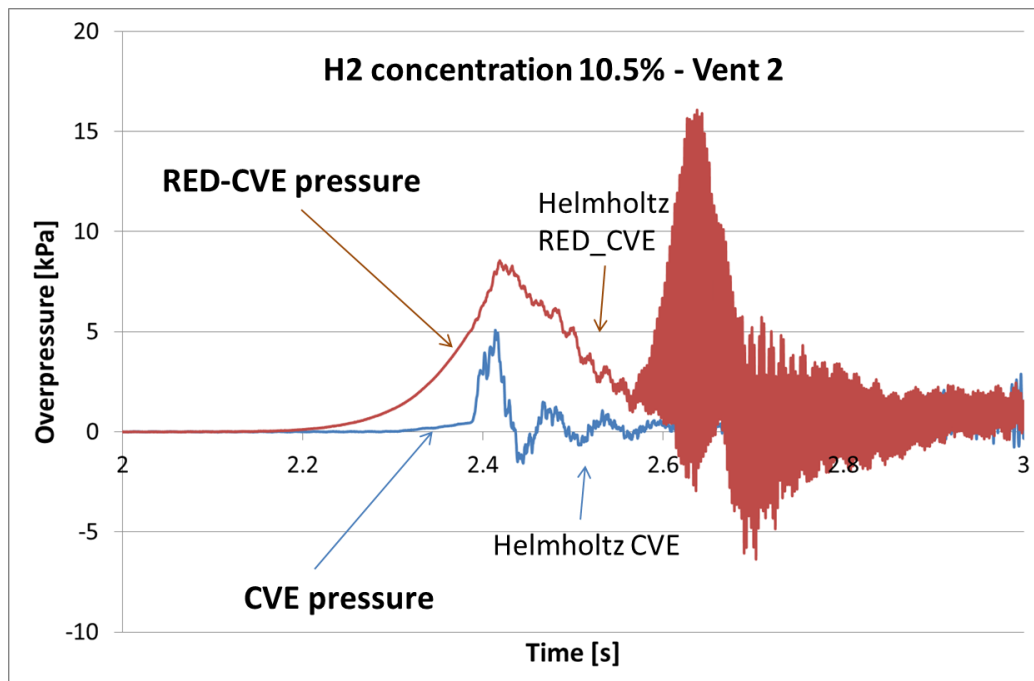


Figure 6 – Pressure-time history of RED-CVE and CVE facility for test RED30 ignited inside the RED-CVE box

After the ignition the pressure started to rise inside the small box, while due to the small vent of the RED-CVE the pressure rose inside the facility after a delay (the pressure transmitter of the bigger volume is located on the wall of the facility opposite the vent). As soon as the vent opens the pressure in both of the environments (CVE and RED-CVE) dropped (see Figure 6). It can be noted how the low frequency Helmholtz oscillation affected each volume with their own characteristic frequency. Over these low frequency oscillations other were superimposed, which frequency could be related to the resonant mode of the enclosure. Helmholtz oscillation, as well as resonant mode of the enclosure, tended to be dumped out and did not really interact with the flame front in the first stage of the deflagration. As soon as the flame reached the vent in the RED-CVE box, anyway, pressure oscillations at frequency of the resonant mode started to interact with the flame front. A detailed analysis of the frequencies shows that these oscillations in the first stage overlapped the low frequency Helmholtz oscillations with amplitude 0.1 kPa, where the Helmholtz had amplitude of 0.5 kPa, resonant frequencies being 320 Hz. As the deflagration progressed, after the flame reached the vent, the oscillations increased in amplitude meaning the interaction between the acoustic waves and the flame front started to play an important role in the pressure build up. During the progress of the deflagration the oscillation increased its frequency in the time interval between the flame front reaching the vent and approaching the walls at the end of the deflagration. The initial frequency of 320 Hz reached 390 Hz. This result may be explained taking into account the increasing average sound speed inside the enclosure that is influenced by the increasing pressure as well as by the progressive filling by combustion products at higher temperature and lower density with respect to the unburned mixture. As a matter of fact the amplitude of the oscillations tended to increase at the same time when the frequency increased, than after the pressure peak was reached, when the flame extinguished, the oscillations were attenuated maintaining the same frequency measured during the peak. Similar results were reported by Tamanini [3].

Correlate the frequency of the observed oscillations with the calculated vibrational modes of the chamber is not an easy task since the sound speed inside the volume cannot be assessed with certainty. As a matter of fact, in order to calculate the time needed by a perturbation such as an acoustic wave to be reflected by a wall and reach the opposite one we should know the distribution of burned and unburned mixture inside the chamber; as well as the sound speed in the unburned mixture and in combustion products that in turns depends on hydrogen concentration.

Using a generic method for calculating the properties of combustion products [14], sound speed had been be estimated for the environment completely filled by combustion product at atmospheric pressure, see table 1.

Table 1. Estimated sound speed for different H<sub>2</sub> concentrations

%vol. H <sub>2</sub>	E.R.	Adiabatic Flame T [°K]	Sound speed [m/s]
9	0.24	1010.6	651.7
10	0.2693	1087.4	677.9
11	0.3	1165.5	703.8
12	0.3305	1240.73	728.3

An air cavity in the shape of a rectangular box has a sequence of nonharmonic resonances. In such a case the walls are nodal points, and there are standing waves between two parallel walls and mixed standing waves involving several walls. The frequencies of such standing waves are given by the relation:

$$f = \frac{c_0}{2} \sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2}$$

Where  $c_0$  is the speed of sound;  $l_x$ ,  $l_y$ , and  $l_z$  are the dimensions of the environment and  $N_x$ ,  $N_y$ , and  $N_z$  are any integers. The acoustic response of the two chambers would depend on the sound speed, in table 2 and 3 results calculated using the formula are listed for different sound speed.

Table 2. Acoustic modes in RED-CVE box for different sound speed

Sound speed	1 <sup>st</sup> [Hz]	2 <sup>nd</sup> [Hz]	3 <sup>rd</sup> [Hz]
650	369	738	1108
700	398	795	1193
750	426	852	1278
800	482	965	1363

Table 3. Acoustic modes in CVE facility box for different sound speed

Sound speed	Resonances [Hz]					
[m/s]	1 <sup>st</sup> Lateral	1 <sup>st</sup> Vertical	2 <sup>nd</sup> Lateral	2 <sup>nd</sup> Vertical	3 <sup>rd</sup> Lateral	3 <sup>rd</sup> Vertical
650	106	114	213	229	320	344
700	115	124	230	247	344	371
750	122	132	245	265	368	397
800	131	141	262	283	393	424

The estimation of the calculated frequencies, despite the approximations, can be related with the measured frequencies in the RED-CVE small box, see Figure 7.

To give better evidence on the behaviour of the pressure oscillations with regard to their increasing frequency, the Figure 7 shows the results, in the range where the frequency had maximum amplitude, of the analysis performed on the overall pressure-time history measured inside the RED-CVE box for 5 tests with ignition located inside the box itself. The picture shows the presence of various peaks characterized by increasing amplitude. Performing this analysis with consecutive “time windows” selected during the progress of the deflagration it can be established that the peaks, represented in Figure 7, correspond to the overlap of

frequencies that characterize the oscillation in consecutive periods. It has to be noted that in tests at higher concentrations, the frequency of the oscillation is also higher. This behaviour being reasonable considering that higher  $H_2$  concentrations results in higher combustion product temperature and hence higher sound speed.

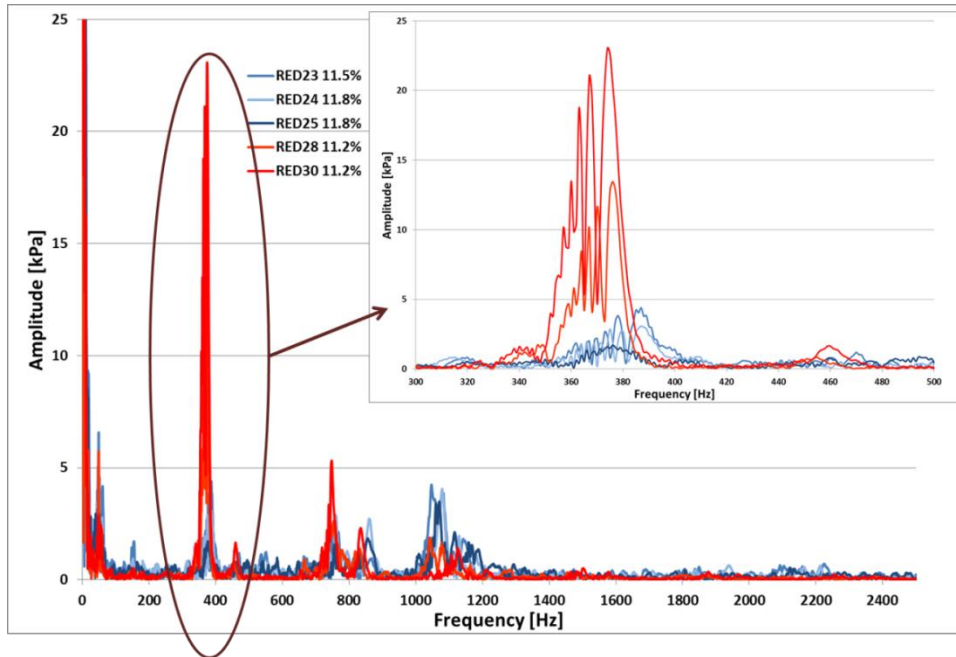


Figure 7 – Analysis of pressure oscillation inside the RED-CVE box in the frequency domain for tests in configuration 7 and ignition inside the box

The amplitude of the oscillations obtained for tests performed with RED-CVE concentration 11.2% were higher than the one obtained in tests which concentration is higher 11.8%. Similar behaviour was reported by Dorofeev et al. [1] comparing results of tests with  $H_2$  concentrations 12% vol and 15% vol. The authors ascribe the higher coupling between the flame-acoustic oscillations at lower concentrations either with the increased thermal-diffusion effects or with the fact that the lower flame-speed of the leaner mixtures allows the oscillations to grow in amplitude for a longer time before the flame reaches the walls of the chamber.

Pressure-time history for test RED15 is provided in Figure 8, where the selected time window is centred in the phase where acoustic oscillation started to appear up to the moment when the flame reached the walls. Evidence of the increasing frequency of the acoustic oscillation can be clearly identified with the naked eyes in the enlarged graph.

The graph of test RED15, Figure 8, represents the pressure behaviour inside the small box for a test where the ignition took place in the CVE test facility, and precisely on the wall opposite the vent. The average concentration was 9.5% in the CVE facility and 10.1% inside the box. After the facility's vent opening pressure peak was attained, the pressure rose again since the flame front was influenced by the turbulent flow field generated by the flow of unburnt gases leaving the vent area. When the flame front reached the vent area a second minor peak was attained and pressure oscillation were triggered inside the bigger volume following the scenario mentioned earlier. At this stage the flame front did not yet entered inside the RED box, the pressure time history inside the box was following the pressure changes in the facility to which Helmholtz oscillation provoked by the movement of air through its vent were superimposed (left part of the upper graph in Figure 8).



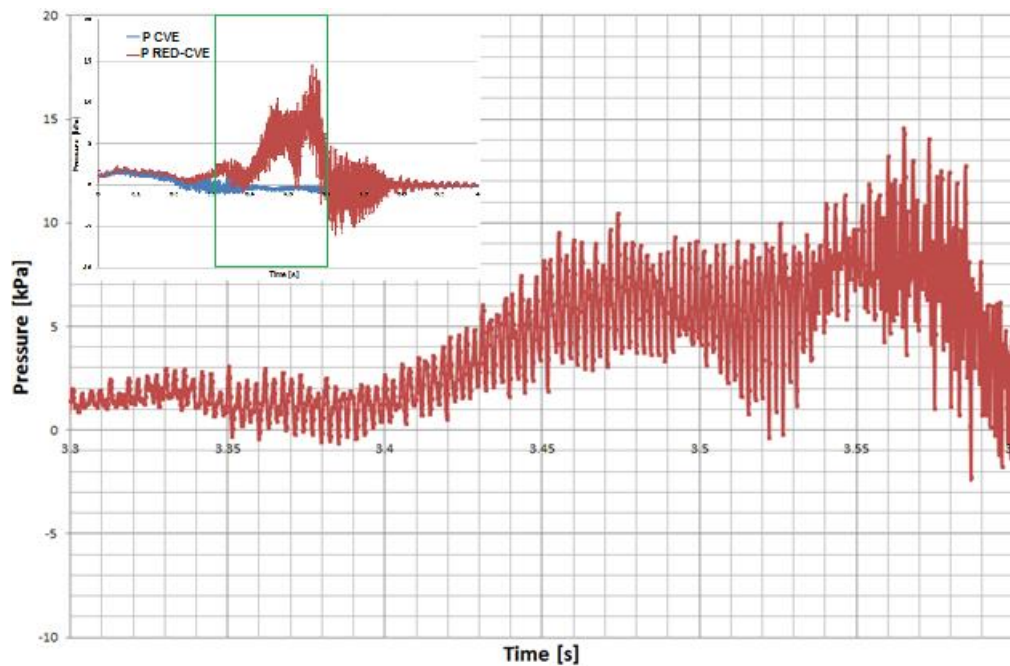


Figure 8 – Pressure time history for a flame entering in the RED-CVE box from the vent area (Test RED15)

In fact, in this case, due to hydrodynamic movement that dragged the flame front towards the vent, the flame entered the box after it had already reached the vent area of the main facility. The flame front was then already affected by the pressure oscillation generated outside the box when it entered inside the smaller volume. The first part of the enlarged graph of Figure 8 shows how this oscillatory behaviour started to interact with the flame front increasing its amplitude as well as its frequency while the flame progressed inside the box. When the pressure reached the plateau between 3.45 and 3.5 sec of Figure 8, the flame burning regime changed abruptly increasing its frequency. In fact the slight decrease of the overall pressure recalls the situation described earlier where the flow rate of combustion products exiting the vent becomes higher than the amount produced by the flame front, and, as in the case described for internal ignition, the flame becomes influenced by acoustic oscillation having frequency characteristic of the resonant response of the chamber. The frequency of these oscillations were similar to the ones measured in the cases described before, and higher than the one produced in the CVE facility.

In fact, as a general behaviour, in tests where the flame front entered in the box through the opening the pressure oscillation measured had comparable frequency with the one generated outside the box in the early stage. Then, during the progress of the deflagration, the frequency increased. This increase of oscillating frequency can be clearly identified, but as a general rule, the amplitude of the oscillations was smaller than the one obtained when the flame surface was not affected at all by the expansion of the combustion products. In fact as described for cases where ignition was located inside the vented volume, as soon as the flow rate of the combustion product became bigger than their production, a different burning regime was introduced and oscillation of higher frequencies were prompted having higher amplitude as well, even if the net overpressure became negligible, as showed in the right part of the upper graph in Figure 8.

For tests performed in the empty CVE test facility the correlation of the oscillating frequencies with the acoustic response of the vented volume is not so clear (see Figure 9). The same behaviour has been found independently of the obstacle configuration. A lot of different peaks can be identified during the frequency analysis for the oscillating pressure, this may be due either to the cohabitation of different phenomena generating acoustic waves in bigger environments as well as to reflection and diffraction of the generated acoustic response of the chamber. For tests performed at average concentration higher than 12% vol. a lower amplitude was recorded in the CVE test facility as well, especially concerning the 1<sup>st</sup> resonant mode of the chamber. This behaviour may be due to the fact that the flame front was already touching the walls of the

enclosure when the acoustic waves were prompted inside and the interaction with the flame front took place in the corners of the volume were reflection and refraction of the waves produced higher frequencies.

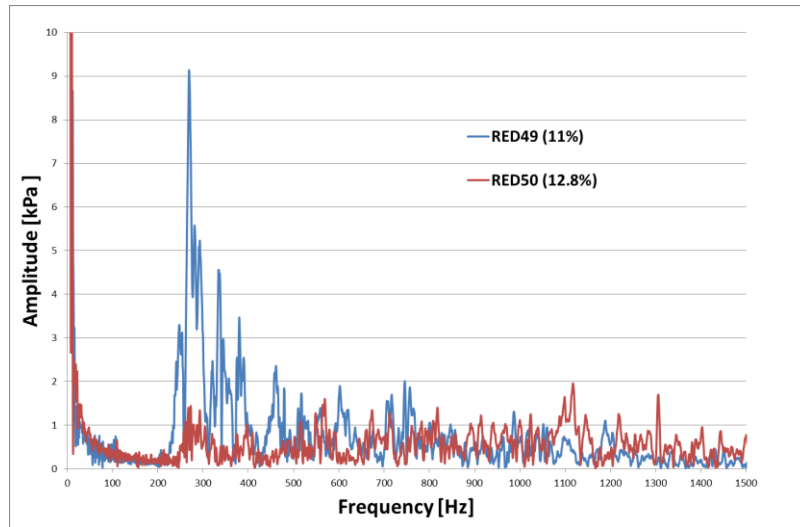


Figure 9 – Analysis of pressure oscillation inside the CVE test facility in the frequency domain for tests with ignition on the wall opposite the vent

For tests where the ignition was located close to the vent the maximum overpressure was comparable with the vent opening pressure. In these cases an interaction between the flame front and the acoustic waves having frequency comparable with the resonant response of the chamber can be identified more clearly, see Figure 10. The amplitude of the oscillations was very low in comparison with the one attained during test with ignition located close to the wall opposite the vent for the same  $H_2$  concentrations. Oscillation had also an higher amplitude for  $H_2$  concentration of 12% than for  $H_2$  concentration of 11.1% (see Fig. 10), showing an opposite behaviour with respect to the tests with ignition located opposite the vent. In this case when the vent opened the flame front was very close to the vent area and it reached it earlier, having no chance to build up significant overpressure inside the vented volume, the interaction between the acoustic oscillations and the flame front may than be weaker due to the weaker acoustic acceleration produced in this case as compared with back wall ignition tests. . This may be also the explanation of the cause of the lower “noise” observed in the frequency analysis for these tests.

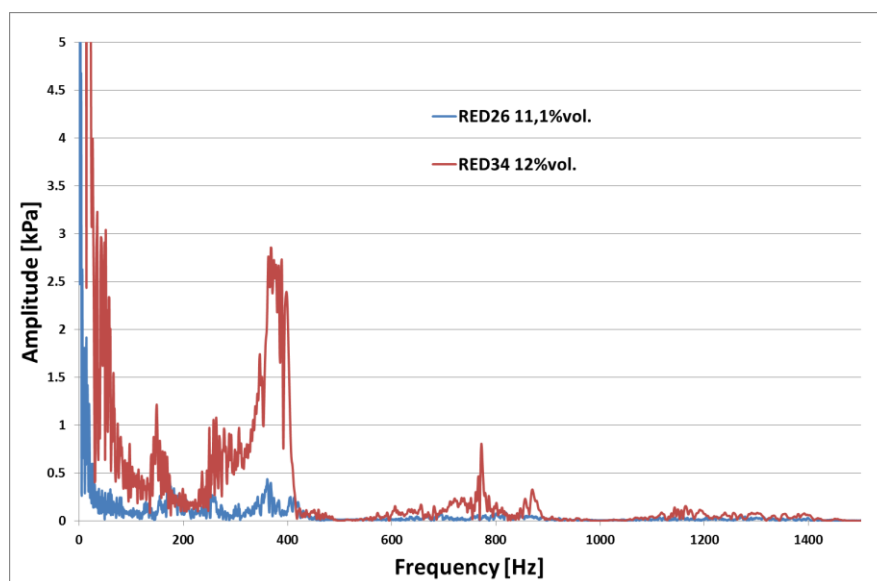


Figure 10 – Analysis of pressure oscillation inside the CVE test facility in the frequency domain for tests with ignition close to the vent

#### **4. CONCLUSIONS**

Experiments were performed at Scalbatraio laboratory, DICI Department of University of Pisa, to investigate phenomena involved in vented deflagration and analysis was performed with the focus on the interaction between acoustic waves and the flame front. The interaction in different volumes and geometries was investigated for lean hydrogen concentrations varying from 7% to 13% vol.

Results for tests with ignition located on the wall opposite the vent, supported by video recording of the deflagration, showed that such interaction start to arise when the flame front reaches the vent area. The abrupt increase of discharge rate of burned products may than be claimed to be responsible of triggering acoustic waves inside the vented volume, as well as producing a change in the burning behaviour of the flame front that from this moment is more susceptible to be influenced by acoustic waves. The mechanism of interaction between the flame front and the acoustic oscillation may be due to the acoustic accelerations.

Following this scenario the flame front can be seen as an interface separating two fluids of different densities. The flame front will than react to the imposed acceleration field as well as it does react to gravity. The presence of an acoustic velocity the flame front is subjected to an oscillating acceleration, when this acceleration is oriented toward the burnt gas the amplitude of the reaction zone will tend to decrease, while when it is oriented towards the unburnt gas, the amplitude of the reaction zone will tend to increase. In this way the acoustic field can thus modulate the total instantaneous heat release rate.

Such interaction is enhanced when the flame front is close to the walls, only in this cases strong pressure oscillation and a significant net overpressure inside the vented volume are generated. For tests ignited on the wall opposite the vent, pressure oscillation had higher amplitude than the ones obtained for ignitions close to the vent for the same hydrogen concentrations. This results being reasonable considering the stronger acceleration generated by the burned gas venting when significant overpressure is present inside the enclosure like in this case.

Results shows that the flame front can interact with acoustic waves externally imposed, as in the case where the flame front entered inside the smaller box being already affected by acoustic response of the main facility. While the flame front progressed inside the enclosure the oscillating frequency tended to increase, as well as the amplitude of the oscillation, both frequency and amplitude being anyway smaller if compared with the one reached in the internal ignition scenario. In this case, when the production of the combustion products became smaller than the amount exiting the vent a new burning regime was introduced were the frequency was comparable with the resonant response of the enclosure and amplitude of the oscillation increased.

In environments of higher volumes the frequencies of the oscillation showed much more “noise” if compared with cases were smaller volumes were under investigation, this behaviour may be due to the mechanism of reflection and refraction of the waves in bigger environments.

Vent opening can also trigger the resonant response of the chamber as well as Helmholtz oscillations inside the enclosure, nevertheless in case of low strength vents the generated acoustic acceleration are weak and the flame front is still expanding far from the vent area, hence no substantial significant interaction with the flame front is found.

#### **5. ACKNOWLEDGMENTS**

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